LightingDemo

Controlling High Power LEDs using DMX512 and DALI

MicroAPL welcomes comments and suggestions. These and any error reports should be sent via our web site: http://www.microapl.co.uk/lightingdemo

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Introduction

Safety Warnings

Do not look directly at high-brightness LEDs unless they are fitted with a suitable diffuser. Some makes of LED are very bright and could cause damage to your eyes if you look at them for a long period.

The high-power version of the High Brightness LED Driver board uses large currents. For example the Luminus PhlatLight CBM-380 can take up to 32A. Handle with care.

This application note is written to accompany the Freescale Semiconductor, Inc reference design for high-brightness LED control, and describes an application called *LightingDemo*.

LightingDemo allows you to control one or more high-brightness LEDs using a PC. It demonstrates how the Freescale Lighting Controller board can be used to control one or more LED slave boards using either of two industy-standard protocols, DMX512/RDM and DALI.

Full source code of the software running on the controller and LED boards is provided.

The application note covers the following topics:

- Configuring the boards and installing the *LightingDemo* application on the PC
- Using the *LightingDemo* application.
- Detailed discussion of the source code of the software running on controller and LED boards.

Configuring the Boards

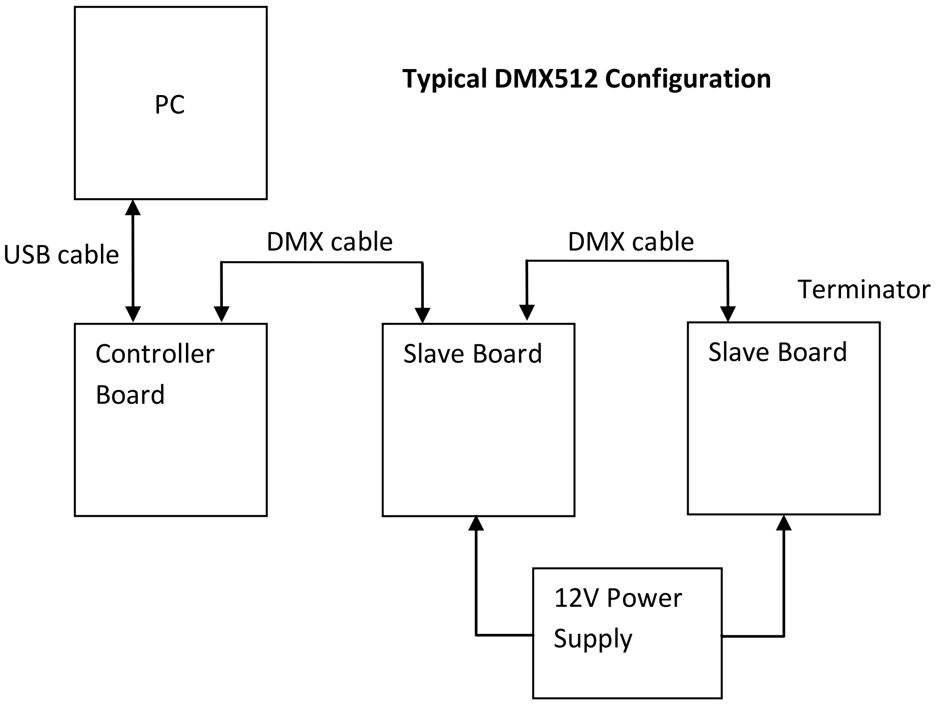
Note: Don't connect the controller board to the PC yet. Because the act of connecting the board will cause the PC to look for new driver software, this step is best delayed until the section "Installing the *LightingDemo* Application".

The *LightingDemo* application requires the following:

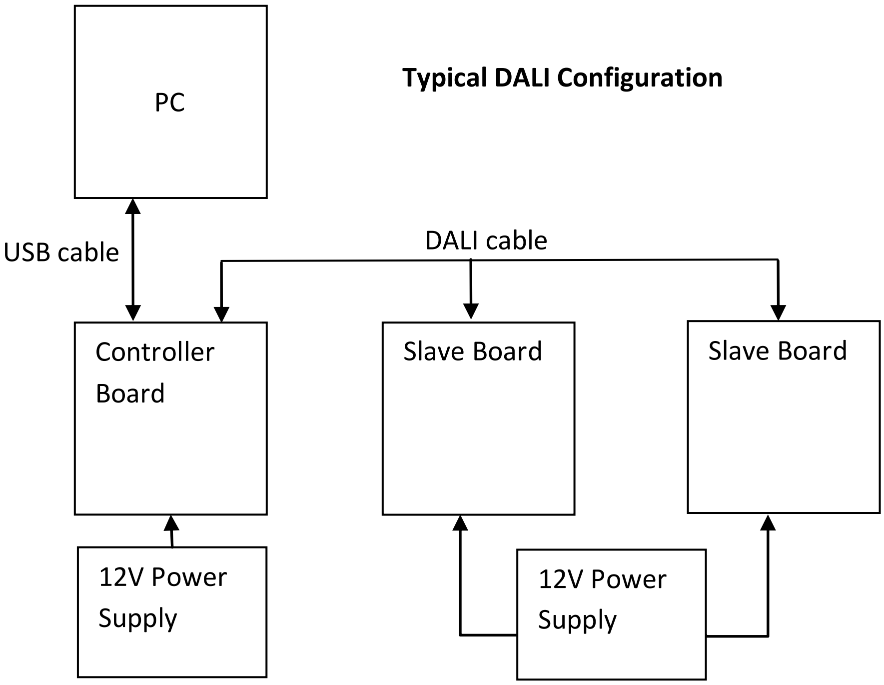
- A PC running Windows XP or Windows Vista 32-bit editions, with .NET framework version 3.0 or later installed
- One Freescale MCF52259 Lighting Controller (the *controller* board)
- One or more Freescale High-Brightness LED Driver boards (the *slave* boards).

The boards must have the correct software installed and be jumpered correctly (see below).

A typical DMX512 configuration is shown below. Note that the Controller board gets its power from the USB connection and does not require a separate power supply, and that the last slave board on the DMX512 link requires a terminator.



A typical DALI configuration is shown below. In this case, the controller board requires an external 12V power supply to drive the DALI link.



Choice of DMX512 or DALI protocol

The *LightingDemo* application allows you to control the high-brightness LEDs using either the DMX512 or DALI protocol. The choice of which protocol to use is determined by the settings of switches on the Controller and Slave boards.

Controller Board:

Set the DMX/DALI switch appropriately

Slave Board:

Set the Mode switch as follows:

1	:	DALI
2	:	DMX512

Notes: This choice determines whether the controller board talks to the slaves through the DMX or DALI interface. It does not affect the connection between PC and controller board, which uses a simple proprietary message format sent over USB.

For demonstration purposes you can connect the boards together using both DMX512 and DALI cabling. You can switch between DMX and DALI at any time without re-booting the boards or re-launching the *LightingDemo* application, simply by changing the switches on the boards. After changing the switches, repeat the device discovery process using the “Repeat Search for Devices” button in the *LightingDemo* application’s Devices window.

Specifying the type of LED

There are two ten-way switches marked 10's and 1's on the slave boards. Together these allow you to specify one of 99 different types of high-brightness LED. At the time of writing the possible values are:

1	:	Philips Lumileds Luxeon Rebel RGB + Cool White
2	:	Luminus PhlatLight CBM-380

This information is used to determine how to drive the LEDs: maximum current, colour balance, etc.

Note: The values above correspond to the <id> tag in the XML descriptions of LED characteristics stored on the slave board.

Specifying a unique DMX512/RDM UID

Every board which implements the Remote Device Management (RDM) protocol extension to DMX512 **must** have a Unique ID (UID). The UID is a 48-bit number consisting of a 16-bit ESTA-assigned Manufacturer ID and a 32-bit device ID.

If you are building a product based on the Freescale Reference Design you should complete the following steps:

1. Apply to ESTA for a unique Manufacturer ID
2. Ensure that every device you manufacture has a unique device ID.

Two devices with the same UID on the same DMX512 lighting circuit will fail to operate properly.

For the Reference Design, the device portion of the UID on the slave boards is assigned a value from 0 - 9 based on the ten-way switch labelled 100's. You must make sure that every board has its 100's switch set to a different value.

For the Reference Design, the controller UID is hard-coded.

> **Note:** Use of the 100's switch to assign the slave board UID is done here for convenience, as is the hard-coded UID used by the controller board.
>
> For a shipping product it's not an acceptable solution; you need to ensure that each device manufactured has a unique ID stored in Flash.

Installing the *LightingDemo* Application

Requirements

The *LightingDemo* application runs under 32-bit versions of Windows XP or Vista. It requires the .NET framework version 3.0 or later, which is always present under Vista but may require installing under XP.

Installation of the *LightingDemo* application consists of two parts: installing the application and installing the USB driver. The easiest way is to install from CD using the following steps:

Installing from CD

1. Start with the controller board not connected to the PC - i.e. do not plug in the USB cable at this stage.
2. Insert the installation CD. This should cause the installer program to launch automatically
3. When prompted to do so by the installer, connect the USB cable. This should cause Windows to recognize that new hardware has been attached.
4. Windows will locate the USB device driver on the CD and install it automatically
5. Continue with the installation of the application. If you do not have the .NET framework installed, the installer will prompt you to install it. You need to be connected to the net if a download of the .NET framework installer is required.

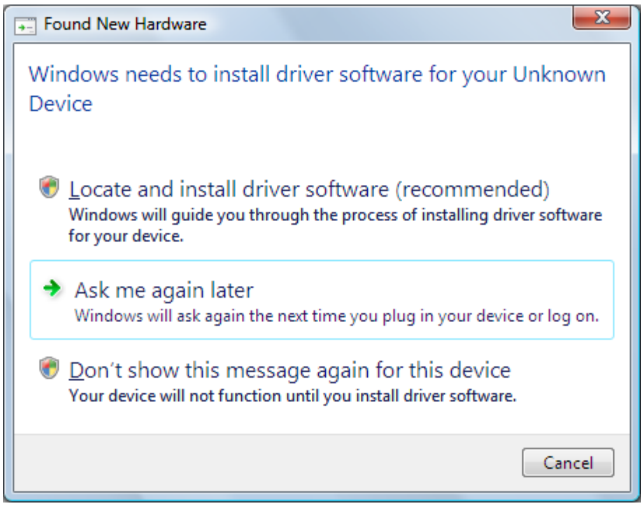
Installing the *LightingDemo* application manually

If you are installing the *LightingDemo* application from an electronic download instead of CD, you can run the installer by launching `setup_freescale_lcb.exe`

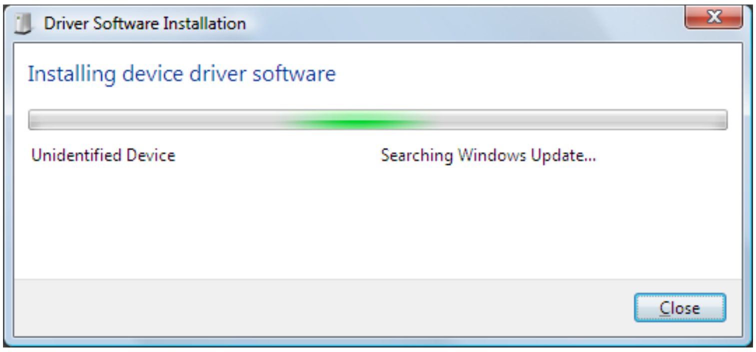
Installing the USB Driver manually

When you connect the USB cable, Windows will recognize that new hardware has been attached and will look for a suitable driver. If you are installing from CD the process should be automatic, but if you are installing from disk you need to use the following steps:

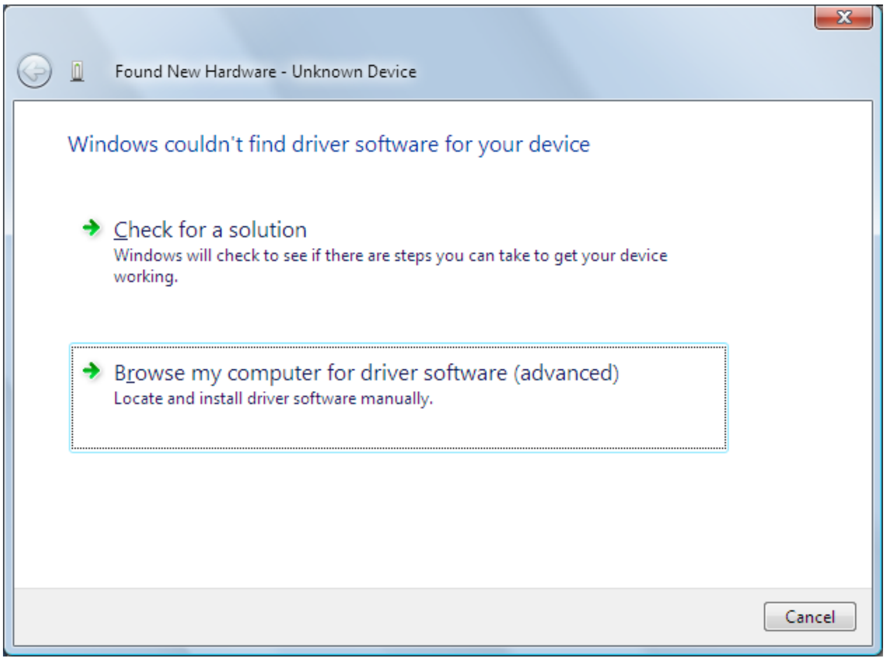
1. Windows will ask whether you want to install the driver:



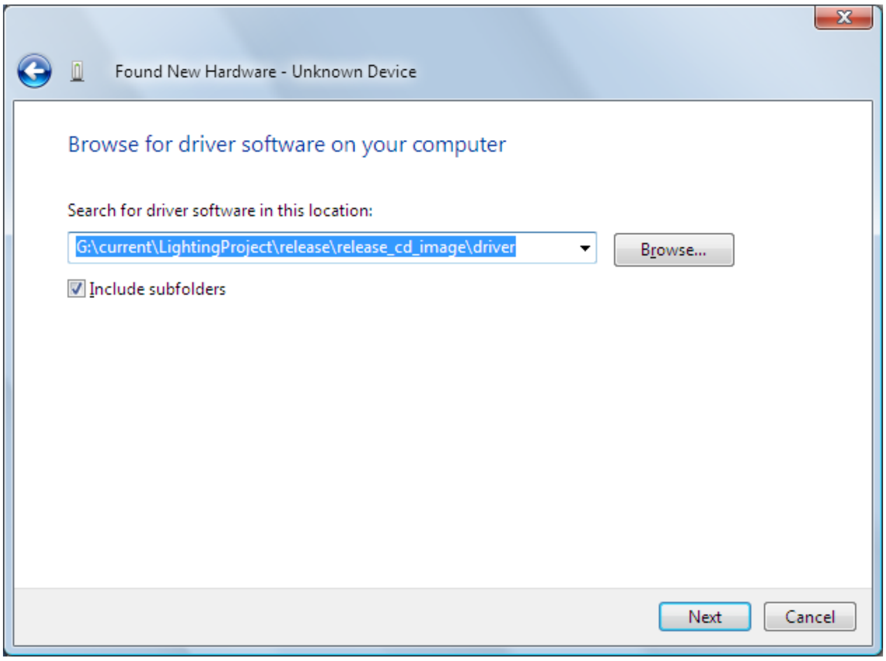
2. If you are installing from a downloaded package, Windows will first look in standard locations for the driver before giving you the opportunity to specify the `driver` folder. This may take several minutes.



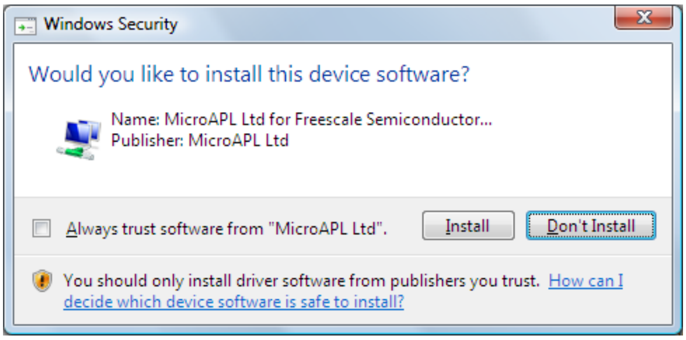
3. Eventually you will be prompted to provide a location for the driver software manually:



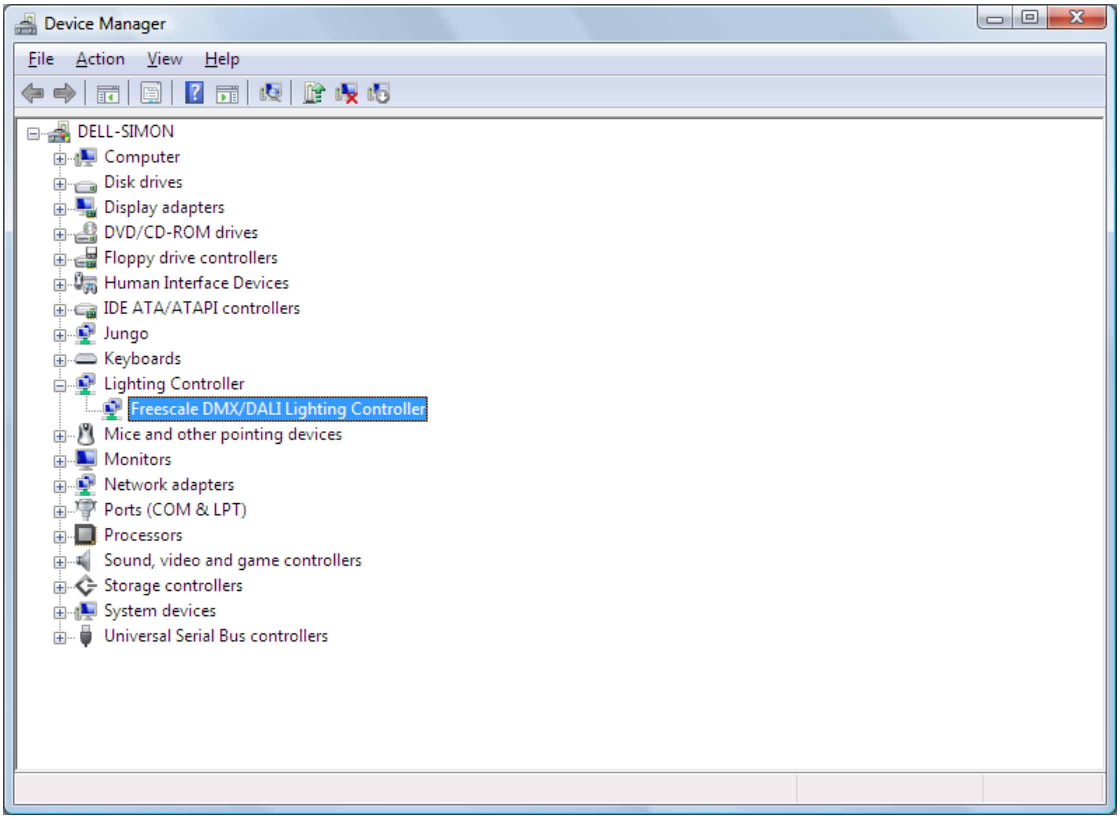
4. Specify the `driver` folder in the *LightingDemo* package:



You should be prompted whether to install the driver:



5. You can verify that the Controller board has been recognized by checking the Windows Device Manager

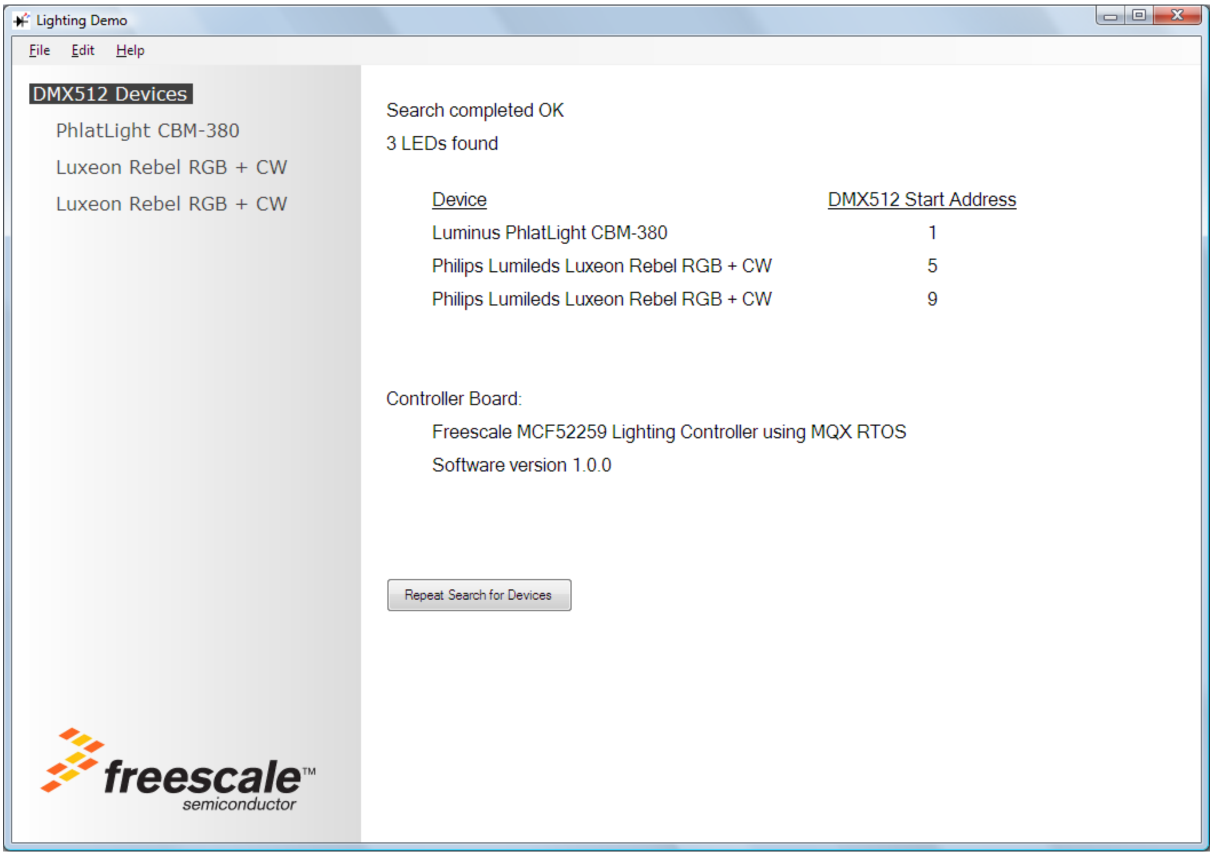


Using the *LightingDemo* Application

Device Discovery

When the *LightingDemo* application is launched it will first attempt to contact the Controller board via the USB connection.

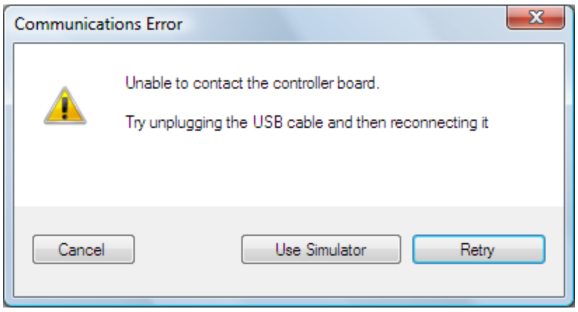
Assuming that all is well, the application will instruct the Controller board to begin a search for connected devices using either the DMX512 or DALI discovery process. Discovery should complete rapidly for DMX512 but may take a few seconds for DALI. After discovery is complete you will see a list of the connected devices:



To begin using a device, select it from the list on the left. You can switch between devices at any time.

Failure to see the Controller Board

If the *LightingDemo* application is unable to contact the Controller board via the USB connection you will see the following dialog:



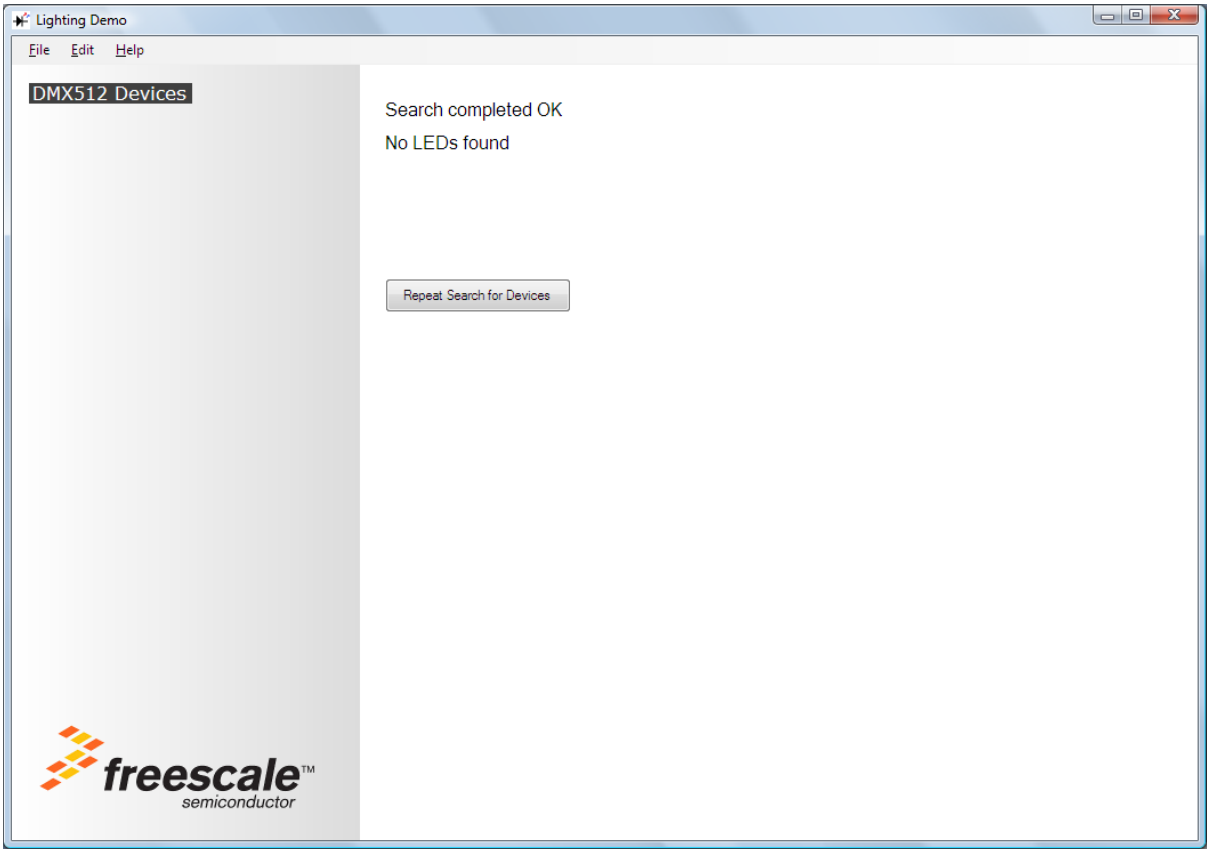
Try unplugging the USB cable and then reconnecting it, which should cause Windows to recognize that it has a Controller board connected. If the problem persists you need to check whether the USB driver installed correctly. See the section “Installing the USB Driver manually” for more information.

The simulator is for use in situations where you don’t have a controller board but are interested in evaluating the *LightingDemo* software. The controller board and slave boards are simulated in software.

The simulator allows you to choose between DMX512 and DALI protocols, investigate the operation of the *LightingDemo* application and view the DMX512/DALI traffic sent over the simulated connection between controller and slaves.

Failure to see the Slave Boards

If the *LightingDemo* application can see the controller board but there is a problem with the slave boards, the list of devices will be empty:



You should verify that the slaves are connected properly, and that the Mode switches on the slave boards are set correctly for DALI (Mode=1) or DMX512 (Mode=2).

In the case of DMX512 you should also:

(a) Make sure that the chain is properly terminated. The last slave board should have a terminator installed on JP1, and the other slaves should have the terminator removed.
(b) Make sure that the switch on the slave board marked ‘100s’ is set to a unique value for each board present.

In the case of DALI, make sure that the controller board has the DALI power supply connected. The board itself is bus-powered from the USB connection, but the DALI interfaces requires a separate power supply.

Device control

Once the device discovery process has successfully completed, you can select a device from the list shown at the left of the *LightingDemo* window. Depending on which protocol you are using, the following options are present

- sRGB Colour Space control

- CIE 1931 Colour Space control

- Direct control
  For DMX512 this option allows you to control the individual colours of a multi-colour LED directly.

  This option is not present for DALI.

- Sensor display
  For DMX512 this option allows you to monitor the on-board sensors on the slave board.

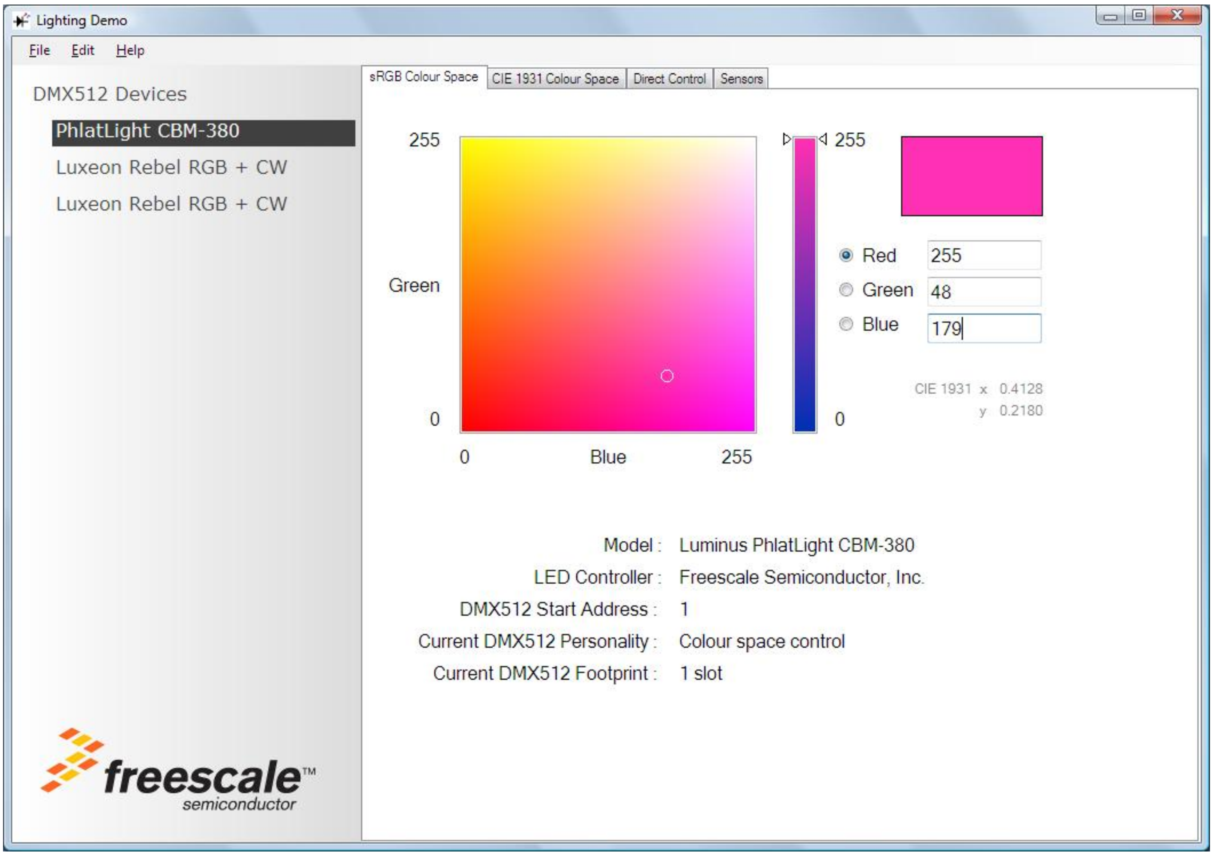
  This option is not present for DALI.

The last two options are not available for DALI because the protocol is much less sophisticated. Using DMX512, multi-byte RDM packets can be exchanged with a slave, for example to inquire about sensor data. By contrast DALI is limited to two-byte messages from controller to slave and one-byte replies.

sRGB Colour Space Control

The sRGB Colour Space is probably the most familiar to users because it's a standard colour space used with computers. A colour defined in the sRGB space has three components: Red, Green and Blue. Each of these is typically represented by an 8-bit value in the range 0-255, leading to a 24-bits-per-pixel representation of colour. For example a 'pure' red is specified as (255, 0, 0)

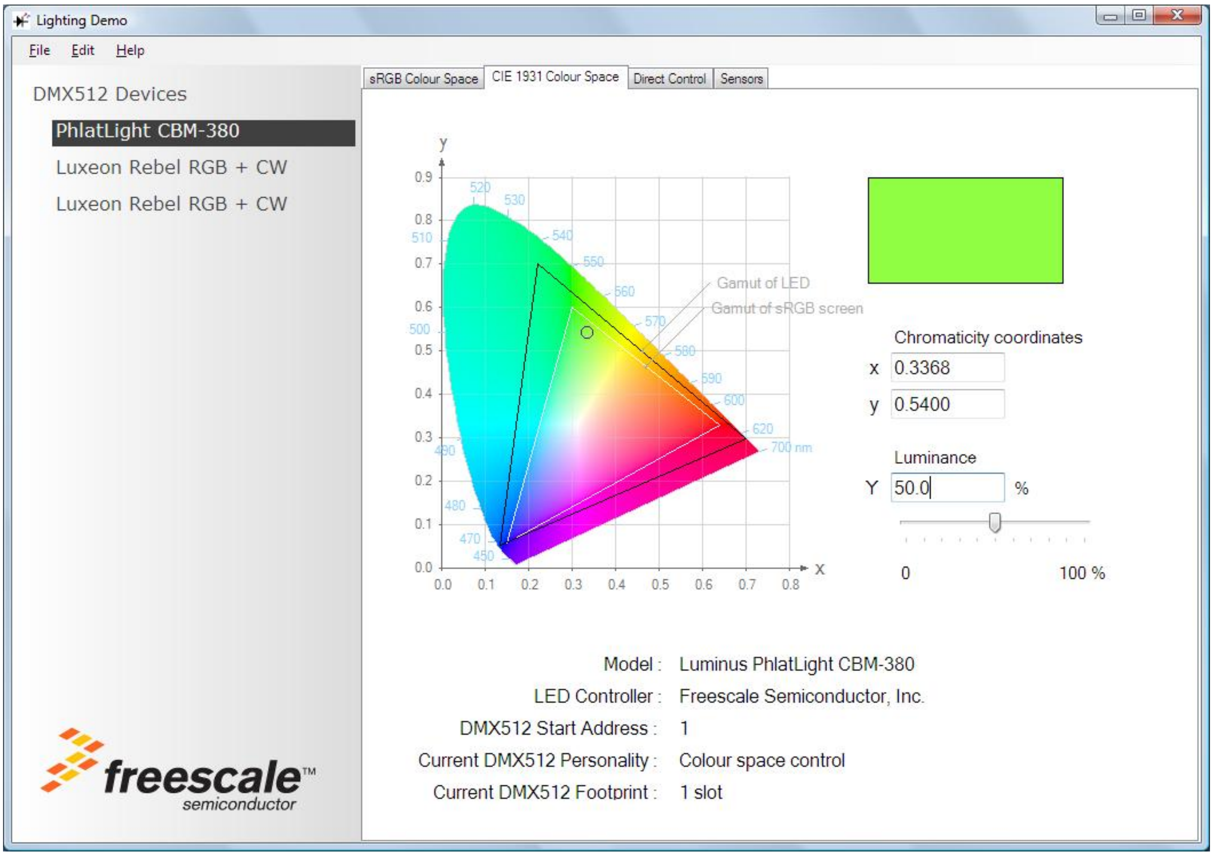
The sRGB Colour Space could be thought of as a three-dimensional cube, with Red, Green and Blue as the axes. In the colour picker show below, the square area represents a slice through the cube showing all possible Green and Blue values when Red = 255.



Note that the primary colours (Red, Green and Blue) of the sRGB colour space are not the same as the Red/Green/Blue primaries used by a typical high-brightness LED. In order to achieve a given sRGB colour using the LED primaries, software has to perform a colour transformation.

CIE1931 Colour Space Control

Although sRGB is widely used for computers, it's not ideal for specifying colours. There are many colours which are visible to the human eye but which cannot be represented accurately on the computer screen. To specify these colours it is necessary to use another Colour Space such as CIE 1931.



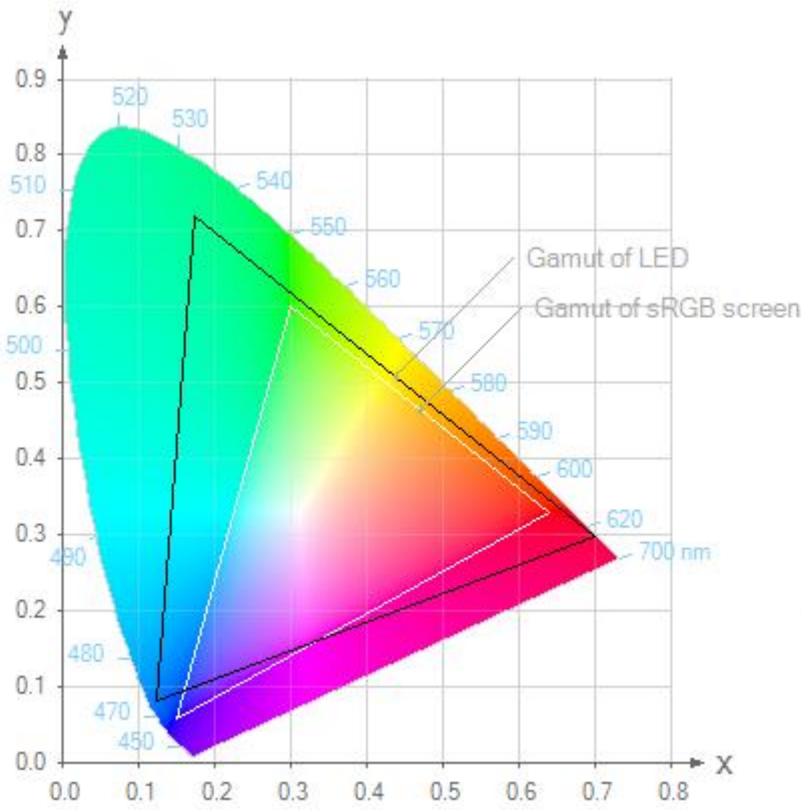
To discuss the CIE 1931 Colour Space we must first define some terms...

Consider two colours like White (sRGB = 255, 255, 255), and Gray (128, 128, 128). In fact, these are normally considered to have the same 'tint' but different 'brightness'. To use more formal language, White and Gray have the same *chromaticity* but different *luminance*.

The CIE 1931 colour space is an attempt to separate the specification of colours into a chromaticity component and a luminance component. Colours are specified in the form `xyY` where `(x,y)` are the chromaticity coordinates and `Y` is the luminance.

You may also see colours specified in the form `XYZ` which is closely related to `xyY`. The `XYZ` values are known as the *tristimulus* values.

The diagram below shows the possible chromaticity values `x` and `y` from 0 to 1. The coloured horse-shoe shaped area represents all the colours which the human eye can see. The outer curve is the known as the spectral locus and shows single-wavelength colours in the range 380 - 700 nanometres.



Note that not all colours in the coloured area can be accurately shown on the computer screen or the printed page. The white triangle shows the 'gamut' of the sRGB Colour Space: the three corners of the triangle correspond to the Red, Green and Blue primaries used by sRGB, and colours outside the triangle cannot be shown accurately on screen.

Similarly the black triangle shows the gamut of a typical three-colour LED (in this case a Philips Lumileds Luxeon Rebel). Some colours that are within the gamut of the LED are outside the gamut of sRGB and vice-versa.

Given two corners of a triangular gamut, any colour on the line connecting the corners can be produced by a combination of the two corresponding primaries. Any colour within the triangle can be produced from some combination of all three primaries.

The *LightingDemo* application allows you to specify a colour by selecting its `(x,y)` chromaticity coordinates and a `Y` luminance value. For the luminance the possible values range from 0 - 100%, where 100% is the maximum brightness that can be achieved for the specified colour. This is affected by a number of considerations:

- Different LED packages from different manufacturers are capable of producing different levels of brightness

- The luminous flux produced by the different primaries in an LED package varies. For example, the green primary is typically much brighter than blue. It follows that the LED can produce a pure green at a much higher luminance than colours which mix green and blue.

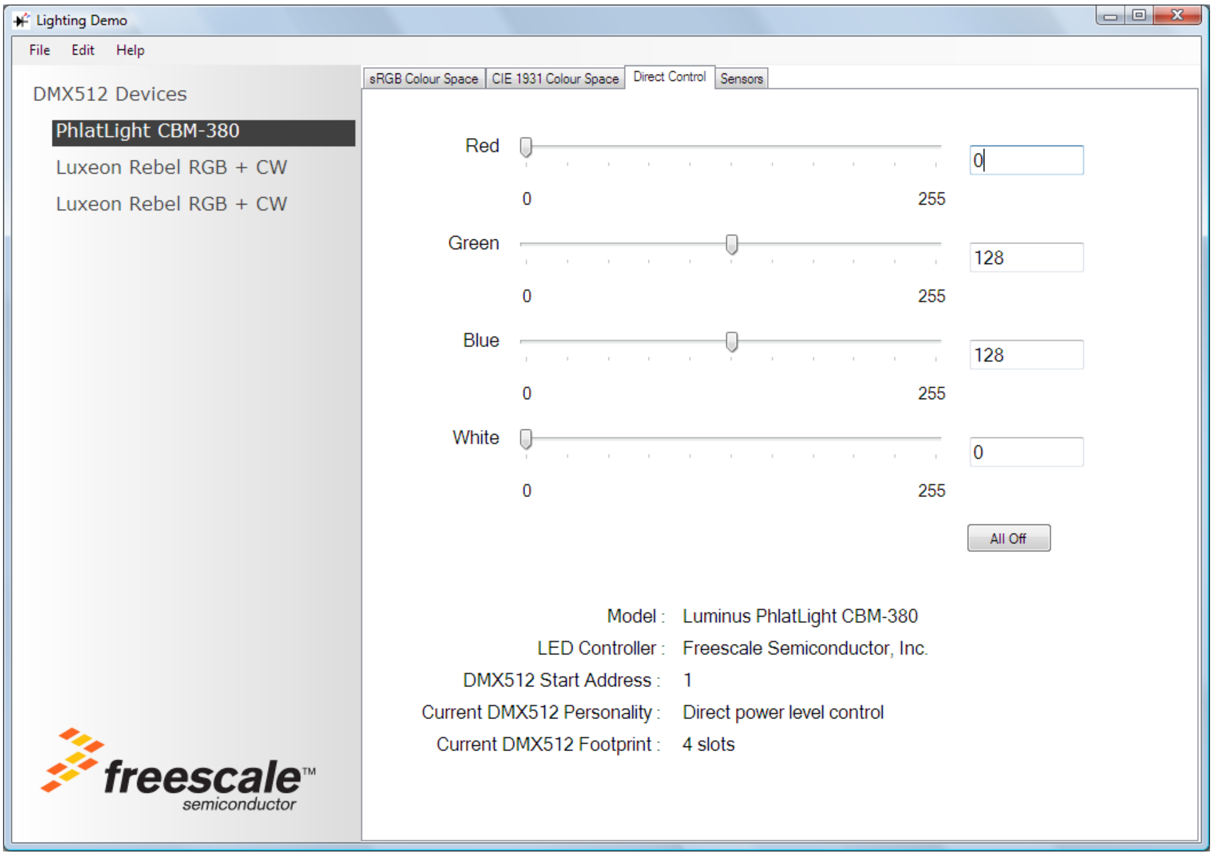
- For some LED packages there is a limit to the total current that can be safely delivered to the LED. For example a Luminus PhlatLight CBM-380 can take 12A for Red and Green, 8.1A for Blue and 9A for White, but the combined current must not exceed 32A in total.

The Y luminance value thus represents a percentage of the maximum theoretical value for the selected LED and colour. The actual lumens may be reduced: if the slave board detects that the LED package is in danger of over-heating it will reduce the power to safeguard the device.

In a system with more than three primaries (e.g. Red, Green, Blue and White), a typical colour can be produced in more than one combination. For example, it might be produce-able using Red + Green + Blue, and also Green + Blue + White. In this case, the software on the slave board calculates the maximum luminance that can be achieved using some combination of both solutions.

Direct Control

If you are controlling the LED using the DMX512 protocol, the *LightingDemo* application also allows you to specify the power delivered to the LED primaries directly.



The Remote Device Management (RDM) extension to DMX512 allows a slave device to have multiple personalities, and the controller can instruct it to switch between them.

In the Freescale implementation, the slave board has two personalities:

(a) In the first personality, the slave board only occupies a DMX512 footprint of one slot. Standard DMX512 packets are used to send a luminance value in the range 0 - 255, corresponding to the 0 - 100% luminance discussed above.

In this personality, colour information is sent using a manufacturer-specific RDM packet bearing `x` and `y` chromaticity values.

This personality is used by the sRGB and CIE 1931 Colour Space options.

(b) The second personality allows the controller board (and hence the *LightingDemo* application) to drive the primaries of the LED directly.

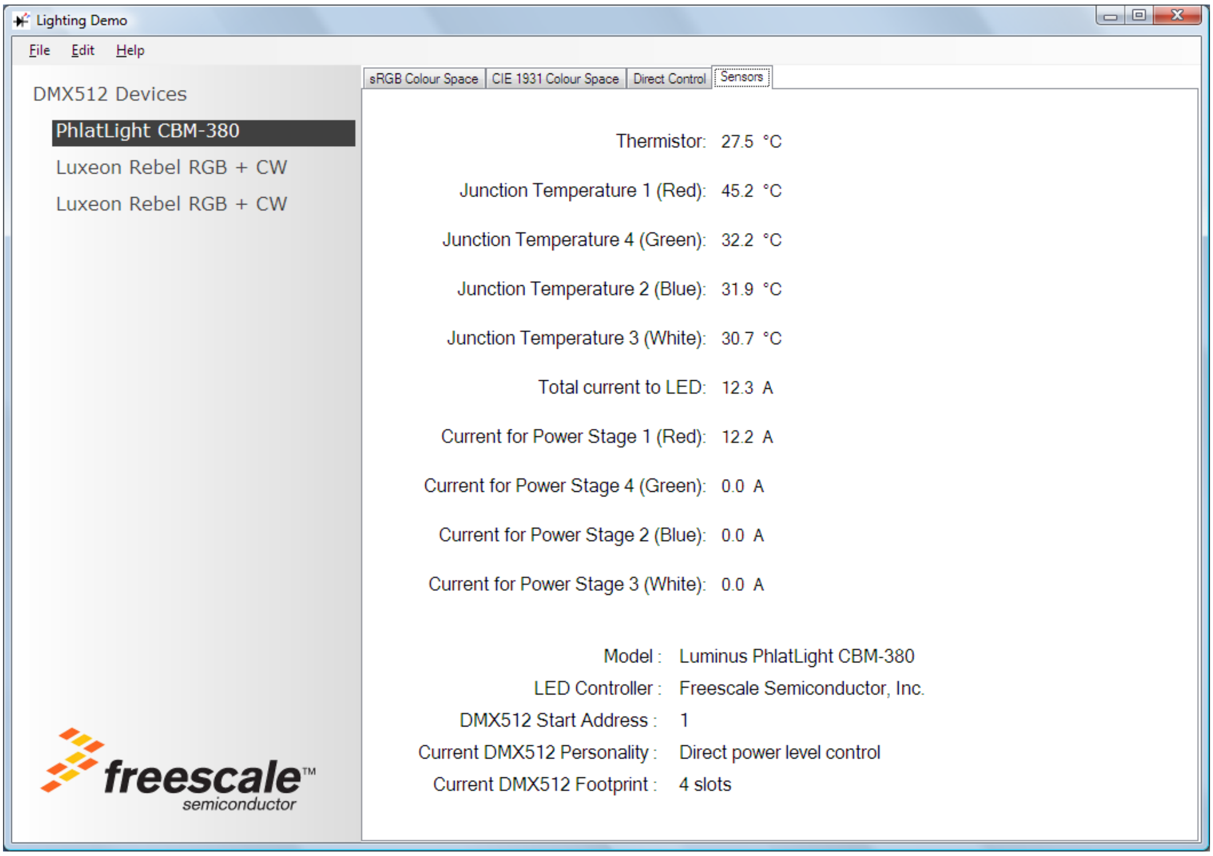
In this personality, each primary occupies one DMX512 slot. The slot value in the range 0-255 can be used to vary the duty cycle of the PWM signal sent to each LED channel, thus controlling the amount of power.

The slave software will still ensure that the LED is not driven at power levels which could damage it.

Sensor Display

Using the DMX512 Remote Device Management (RDM) protocol it is possible for the controller board to monitor the on-board sensors on the LED slave board.

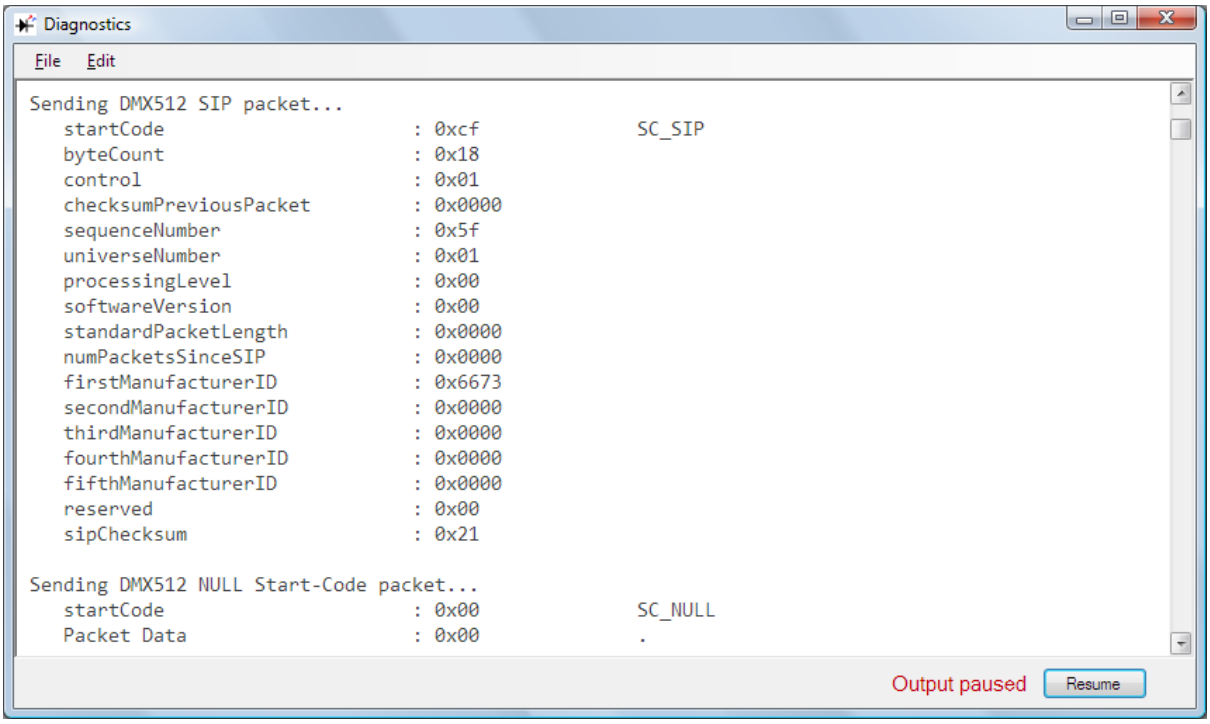
The sensors available depend on the type of slave board and the LED package used. Low-power boards only support a thermistor, whereas high-power boards also allow the current consumption to be monitored.



The thermistor reading measures the temperature of the heat sink. Software on the slave board uses this value together with the power consumption to calculate the junction temperature(s) within the LED package and so regulate the power in order to prevent damage to the LED through over-heating.

Diagnostics

The Diagnostics window allows you to see the traffic exchanged between the controller and slave boards. Packets are shown in an annotated form as follows:



The DMX512 protocol requires that a NULL Start-Code packet (a standard DMX512 packet) is sent at least once a second. This can make it difficult to see the contents of the Diagnostics window because they keep changing, so the Pause / Resume button can be used. The Pause function stops the window from updating; it has no effect on the DMX512 traffic, which continues to be generated.

Software Overview

The remainder of this document will describe the source code used to implement DMX512/RDM and DALI lighting control. The software for the application consists of three parts

(1) The *LightingDemo* application itself, running on the PC.

    The source code of this application is not provided. Please contact MicroAPL Limited if you have any queries regarding this software.

    The application is written in C# using the .NET application framework. It communicates with the Controller board via USB using a simple proprietary protocol (not DMX or DALI)

(2) The software running on the Controller board

    Full source code of the Controller board application is provided. It is written in C and compiled with the CodeWarrior for ColdFire tool chain. The free, open-source MQX operating system is also used, mainly to implement the USB connection.

(3) The software running on the Slave board(s)

    Full source code of the Slave board application is provided. It is written in C and compiled with the CodeWarrior for Microcontrollers tool chain (The microprocessor used on the board is a Freescale MC13213 processor). No operating system is used.

The software on the Controller and Slave boards can be modified to use only the DMX512/RDM protocol, or only the DALI protocol, without much difficulty.

Note that some source code files are shared between Controller and Slave implementations. For example the file `dmx_support.c` contains support routines used by both boards for DMX512.

Documentation

A very useful source of documentation on the individual routines is the subroutine header in the source file itself. For example:

```
/**********************************************************************
*       dmx_controller_init - Allocate and initialise DMX controller    *
***********************************************************************
; Allocates memory for DMX controller device and initialises data structure
;
; Arguments:
;   uint_16     inDeviceNumber          - Physical device to use for I/O
;   uint_8      inUniverseNumber        - DMX Universe Number [1-255]
;   RDM_UID     inUID                   - RDM device UID
;
; Result:
;   DMX_HANDLE  result                  - Handle to DMX device
;
*/
```

Memory Footprint

The following are approximate figures for the memory footprint of the software on the controller and slave boards. They should be taken as a guide only. No attempt has been made to reduce the footprints since they fit comfortably on the target hardware. Contact MicroAPL if memory usage is a concern.

Controller Board

	Code	Data
PC / USB interface	10250	2900
DMX512 code	10050	4300
DALI code	6600	5500
MQX RTOS	63000	1200
Total	**89900**	**13900**

Removing the packet-level debugging code makes the application smaller.

Note that the application makes very little use of the MQX RTOS apart from the USB stack, so it would be possible to run without an RTOS without too much re-coding work.

Slave Board

	Code	Data
Application	7800	410
DMX512 code	9500	10
DALI code	6700	50

LED control	12800	100
Compiler support libraries	8630	2006 (inc. 2000 byte heap)
Other	230	640
Total	**45660**	**3216**

In addition, the slave-board software can be built in a **mini-DALI** version designed to fit in only 8K of Flash and 512 bytes of RAM. This version only allows the LED to be controlled using the DALI protocol. The brightness of the LED can be controlled using the standard DALI command set, but not the colour of the LED. In addition, the software does not perform thermal monitoring of the LED to prevent damage by over-heating, leaving it up to hardware to limit the current to a safe maximum value.

The documentation here will mainly discuss the full slave implementation, not the mini-DALI version, although most of the source code is shared by the two versions.

DMX512 and RDM implementation on the Controller and Slave Boards

On both controller and slave board, DMX512/RDM data is sent and received using a UART operating in polled mode.

The DMX512 protocol can be divided into two parts.

In standard DMX512, each slave device has a start address in the range 1 - 512, and a footprint of one or more ‘slots’. Primary control is achieved by the controller broadcasting NULL Start-Code packets containing up to 512 slot values.

For added reliability, DMX512 controllers can interleave the NULL Start-Code packets with System Information Packets (SIPs) which allows a checksum to be appended to the NULL Start-Code data.

The Remote Device Management protocol (RDM) is an extension to standard DMX512. It allows the controller to send multi-byte messages to an individual slave, and also to get multi-byte replies. In addition, it allows the controller to discover which devices are connected to the DMX512 network.

The application software on the controller board implements both DMX512 with SIP support, and RDM. RDM is used to find out which slave devices are connected, ask them for detailed information about capabilities, and assign DMX512 start addresses.

A DMX512/RDM slave consists of a Root device and optionally one or more sub-devices. The slave board software implements one sub-device, used to control a single multi-colour LED package. In principle the software could easily be adapted to support multiple sub-devices, for example multiple independent white LEDs.

The DMX512/RDM implementation on the slave boards supports two RDM personalities:

(a) `PERSONALITY_xyY_CONTROL`

When configured via RDM to use this personality, the slave board has a footprint of a single DMX512 slot. The controller uses the slot to send a CIE 1931 `Y` luminance value (0 - 255), and sends the `(x,y)` chromaticity values using a separate RDM command.

(b) `PERSONALITY_DIRECT_CONTROL`

In this personality the slave board has a footprint of up to four DMX512 slots, one for each channel that the LED supports. For example an LED with three primaries Red, Green and Blue will have a footprint of three slots. The values in the DMX512 slots are in the range 0-255 and correspond to 0 - 100% duty cycles.

Note that the controller software doesn't perform any special handling for RDM responses from a slave sent with `REPONSE_TYPE_ACK_TIMER` (meaning that the slave isn't yet ready to respond). The Freescale slave-board software never sends this type of response. If required, it can be handled in application code or by a simple modification to the controller routine `rdm_get_response`.

Endian Dependencies

DMX512 SIP and RDM packets use big-endian byte ordering for integer values which are more than one byte wide.

The MCF52259 processor used on the controller board also uses big-endian byte ordering conventions, as does the CodeWarrior compiler used for the slave board.

However, to make the software as portable as possible all multi-byte accesses are done through macros:

```
read_big_endian_u16
read_big_endian_u32
store_big_endian_u16
store_big_endian_u32
```

For example, the following code reads a 32-bit unsigned value and replaces it with another:

```
value = read_big_endian_u32 (pointer);
store_big_endian_u32 (pointer, value+1);
```

DALI implementation on the Controller and Slave Boards

On both controller and slave board, DALI data is sent and received using a GPIO port.

Data is sent using a routine which tightly controls the timing of the generated bi-phase signal to match the DALI specification.

Data is received by using an interrupt service routine which over-samples the signal. The signal has a frequency of 1200 bits per second but it is bi-phase encoded so there are 2400 phases per second. The interrupt frequency is 9600 sample per second - i.e. 4 samples per phase. Software compares the samples to ensure that they match. Because the received signal may vary slightly in frequency or duty cycle, software considers a match of 3, 4 or 5 samples to be acceptable.

The DALI protocol is really designed for controlling single-colour lights which it calls ‘ballasts’. The controller can instruct individual ballasts to light up, change to a specified power level, fade up or down, etc. Ballasts can also be addressed as groups instead of individually, or added to pre-set scenes. The DALI protocol also includes a means for the controller to discover which DALI slaves are connected.

DALI commands from controller to slave are two bytes long, and replies from slave to controller are a single byte (Many commands don’t result in a reply). Each DALI slave has a unique Short Address in the range 0 - 63.

The DALI implementation used by the controller and slave is standard in all respects except for one extension: the standard DALI protocol does not include any way for a controller to instruct an LED to change colour rather than brightness, so a way is needed to achieve this.

In the Freescale implementation, the normal DALI commands affect the *brightness* of the LED - in CIE 1931 colour space terminology, the power level corresponds to the `Y` luminance. (In fact, DALI uses a logarithmic dimming curve, so the value is derived from the log of the luminance).

Since this is the way *all* DALI devices work, it is possible to use a Freescale DALI controller with non-Freescale DALI slaves, and it means that a Freescale slave looks like a standard ballast to non-Freescale controllers.

In order to convey chromaticity information, the Freescale implementation uses a backdoor route to extend the command set. The backdoor makes use of a standard DALI command `DATA TRANSFER REGISTER`, and is invisible to non-Freescale DALI devices.

Because DALI commands are only two bytes long, all DALI slaves implement a Data Transfer Register (DTR). In order to program a setting such as the power-on level of a ballast, the DALI controller sends two 2-byte commands:

```
; Store 99 in the DTR
      DATA TRANSFER REGISTER, 99

; Tell the addressed device to store the DTR as the power-on level
      <address>, STORE THE DTR AS POWER ON LEVEL
```

The backdoor command to set chromaticity information relies on the fact that setting the DTR to one value and then another (without any intervening commands) is both harmless and pointless. No other DALI controllers are likely to do it, and it has no effect on normal DALI slaves.

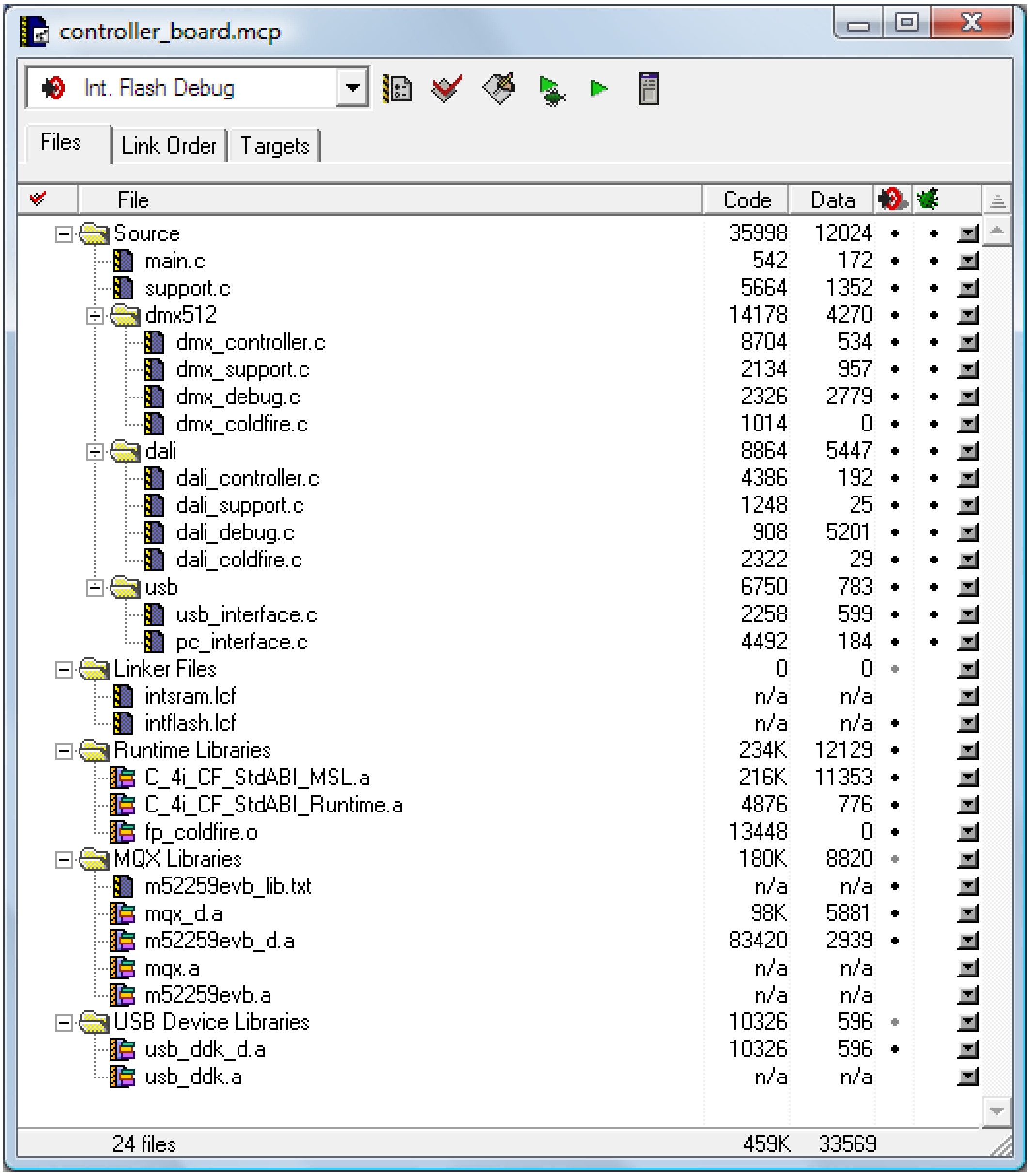
In order to send chromaticity information the controller sequences the DTR through a secret multi-character backdoor key to alert the slave that a chromaticity command is coming. It then uses the DTR to communicate the `(x,y)` chromaticity coordinates to the slave. See the routines `dali_send_backdoor_command` in the controller and `handle_dali_backdoor_command` in the slave for further details.

Controller Board software

The following screen snapshot shows the files used to implement the application on the controller board. If you are using the reference software as a basis for a new stand-alone lighting controller design, it is anticipated that you will

(a) select either DMX512 or DALI and remove the unwanted files, and

(b) concentrate most effort on re-writing the code in the files `usb_interface.c` and `pc_interface.c` to implement the functionality of the new controller



MQX on the controller board

The MQX libraries are derived from the standard MQX 3.3 port to the Freescale M52259EVB evaluation board, with only one change : The board support package `m52259evb.a` / `m52259evb_d.a` has been re-built to use UART2 instead of UART0 as the standard I/O port. This is necessary because the Controller board uses UART0 for the DMX512 connection. UART2 is optionally used for debugging.

To make this change when rebuilding the M52259EVB board support package, edit the file `user_config.h` and change as follows:

```
#define BSPCFG_ENABLE_TTYC       1
#define BSP_DEFAULT_IO_CHANNEL  "ttyc:"
```

By default, UART2 is configured to use

- 115200 baud
- 8 data bits
- 1 stop bit
- No parity
- No handshake

Debugging information for the controller board

A number of support routines like `debug_printf` allow debugging information to be collected.

All calls ultimately call a routine `debug_vprintf` in the file `support.c`. This routine is responsible for outputting the debug text in some form. For example it could send it to the UART2 serial port.

In the current implementation it stores the debug text in a circular buffer, from where the *LightingDemo* application on the PC picks it up via a USB request, and UART2 is not used.

C Pre-processor Definitions for the controller board

The Controller board software can be built in a number of configurations:

- DMX controller, DALI controller or both
- Optional debugging
- Code to run on the actual board, or code running in the 'simulator' option used by the *LightingDemo* application

These build options are controlled by C pre-processor macros.

The following are defined through the CodeWarrior C/C++ Pre-processor Target Settings panel...

(a) To enable/disable DMX512/RDM support

```
#define DMX_CONTROLLER   1
```

or

```
#undef DMX_CONTROLLER
```

(b) To enable/disable DALI support

```
#define DALI_CONTROLLER  1
```

or

```
#undef DALI_CONTROLLER
```

(c) To specify whether the code runs on actual hardware or in the simulator

```
#define CONTROLLER_BOARD  1
```

or

```
#define SIMULATED_BOARD  1
```

Additionally, printf-style debugging information can be turned on and off using the `SUPPORT_DEBUGGING` equate defined in the header file `dali_and_dmx_types.h`.

Using DMX512/RDM on the Controller Board

This section will discuss how to use the DMX512/RDM controller from application software, looking at some of the main routines. For a complete example, see the end of the section.

Initialising the DMX_HANDLE

The public interface to the DMX512 software uses an opaque data type `DMX_HANDLE`. Application software should begin making a call to `dmx_controller_init` to allocate a new handle:

Function Prototype:

```
DMX_HANDLE dmx_controller_init (uint_16 inDeviceNumber,
                                uint_8 inUniverseNumber,
                                RDM_UID inUID);
```

In principle the software could support multiple DMX512 universes if the hardware allowed it.

Initialising the hardware

After the `DMX_HANDLE` has been initialised, the application should call the routine `dmx_device_init` to initialise the hardware interface.

Function Prototype:

```
DMX_ERROR dmx_device_init (DMX_HANDLE inHandle);
```

Note that the controller board software to accompany the *LightingDemo* application allows the user to switch between DMX512 and DALI protocols dynamically. This is achieved by calling `dmx_device_init/ dmx_device_deinit` and the DALI equivalents as appropriate .

RDM Discovery

To perform an RDM discovery process in order to find out which slaves are attached to the DMX512 network, call the `rdm_discovery` routine

Function Prototype:

```
DMX_ERROR rdm_discovery (DMX_HANDLE inHandle,
                         boolval inDoCompleteDiscovery);
```

This will cause the controller software to initiate RDM discovery, searching the 48-bit RDM address space for enabled devices. For each slave that is found, the software will request additional information such as the device manufacturer, number of personalities, footprint, etc.

The result is added to a linked list of all known slaves, in which each item has the following structure. Note that where a slave implements one or more sub-devices there will be one entry in the linked list for the Root device, and one for each sub-device.

```
typedef struct DMX_SLAVE_RECORD {
    RDM_UID     slave_UID;              /* Slave UID */
    uint_16     subDevice;              /* RDM_ROOT_DEVICE, or
                                           sub-device number */
    uint_16     startAddress;           /* DMX512 start address */

    uint_8      currentPersonality;     /* Current personality */
    uint_8      numPersonalities;       /* Number of personalities
                                           supported */
    RDM_PERSONALITY personality [MAX_RDM_PERSONALITIES+1];
                                        /* Personality records.
                                           Note: RDM numbers
                                           personalities from 1 upwards,
                                           so used entries in
                                           this array are in range
                                           1 - numPersonalities */

    uint_8      *slotValues;            /* Array of slot values */
    uint_16     numSubDevices;          /* Number of DMX sub-devices
                                           if RDM_ROOT_DEVICE, else 0 */
    char        *model;                 /* Model description */
    char        *manufacturer;          /* Manufacturer description */
    uint_16     modelID;                /* Model ID */
    uint_16     numSensors;             /* Number of sensors */
    struct DMX_SLAVE_RECORD *next;      /* Linked list of records */

} DMX_SLAVE_RECORD;
```

The following convenience routines allow you to walk the slave list:

(a) Return count of the number of slave records found.

```
uint_32 dmx_count_slaves (DMX_HANDLE inHandle);
```

(b) Return pointer to first slave record, or NULL if no slaves found

```
DMX_SLAVE_RECORD *dmx_slave_list (DMX_HANDLE inHandle);
```

(c) Return pointer to Nth slave (starting from 0), or NULL if no such record exists.

```
DMX_SLAVE_RECORD *dmx_find_nth_slave (DMX_HANDLE inHandle,
                                      int inIndex);
```

Allocation of DMX512 Start Addresses

In order to communicate with a slave through a DMX512 NULL Start-Code packet, the slave needs to be assigned a DMX512 Start Address.

The routine `rdm_allocate_dmx_addresses` will use RDM to allocate start addresses to any slave that doesn't have one, ensuring that no overlapping start address/footprint values are present.

Function Prototype:

```
DMX_ERROR rdm_allocate_dmx_addresses (DMX_HANDLE inHandle);
```

Sending data in DMX512 NULL Start-Code packets

The DMX512 protocol requires that a NULL Start-Code packet is sent at least once a second. It is the application's responsibility to call `dmx_send_NULL_start_code_packet` periodically to ensure that this requirement is met.

Function Prototype:

```
DMX_ERROR dmx_send_NULL_start_code_packet (DMX_HANDLE inHandle);
```

This routine will also cause SIP packets with checksum information to be sent if this option is enabled.

The slot values that are sent in a NULL Start-Code packet are buffered locally by the controller. To change one or more slot values, call the `dmx_set_slot_values` routine.

Function Prototype:

```
DMX_ERROR dmx_set_slot_values (DMX_HANDLE inHandle,
                               uint_16 inStartAddress,
                               uint_16 inNumSlots,
                               uint_8 *inValues,
                               boolval inImmediateUpdate);
```

System Information Packets (SIPs)

The use of SIP packets improves the reliability of DMX512 by adding checksum information, but slightly reduces the maximum throughput. You can control the generation of SIPs using the `sip_set_checksumming` routine. The use of SIPs is recommended in most situations.

Function Prototype:

```
void sip_set_checksumming (DMX_HANDLE inHandle,
                           boolval inEnableDisable);
```

Changing the RDM personality of a slave device

As a convenience, the routine rdm_set_personality can be used to change the current personality used by a slave device. Note that personalities are numbered from 1 upwards in RDM.

Function Prototype:

```
DMX_ERROR rdm_set_personality (DMX_HANDLE inHandle,
                               DMX_SLAVE_RECORD *inSlave,
                               uint_8 inPersonality);
```

Specifying CIE1931 Colour Space values

The routine `rdm_set_chromaticity` allows the application to control the chromaticity and luminance of a slave device. It takes an `(x,y)` chromaticity coordinate and a `Y` luminance value as arguments. The luminance argument is in the range 0.0 to 1.0 to request 0 - 100% of the maximum lumens that the slave can deliver at the requested chromaticity.

Function Prototype:

```
DMX_ERROR rdm_set_chromaticity (DMX_HANDLE inHandle,
                                DMX_SLAVE_RECORD *inSlave,
                                double in_x,
                                double in_y,
                                double in_Y);
```

Sending other RDM commands

Application software can send other RDM commands to a slave device by using the sequence:

```
tx_packet = rdm_make_command (inHandle, ...);

errcode = rdm_send_packet (inHandle, tx_packet);

if (errcode == ERR_DMX_OK) {
    /* Any response? */
    errcode = rdm_get_response (inHandle, tx_packet, &rx_packet, false);
}
```

Note: It is important that software follows the sequence above. A successful call to `rdm_send_packet` will complete *with interrupts disabled*. The expectation is that it will be immediately followed by a call to `rdm_get_response` which re-enables interrupts on completion.

(a) The `rdm_make_command` routine takes the specified arguments and builds an RDM packet ready for transmission. The packet is not quite complete at this stage, because checksum information is not added until `rdm_send_packet` is called.

Function Prototype:

```
RDM_PACKET *rdm_make_command (DMX_HANDLE inHandle,
                              RDM_UID inDestination,
                              uint_16 inSubDevice,
                              uint_8 inCommandClass,
                              uint_16 inParameterID,
                              void *inParameterData,
                              uint_8 inParameterLength);
```

The parameters `inCommandClass` and `inParameterID` specify the RDM command to send, for example `GET_COMMAND` and `SLOT_DESCRIPTION`

For commands which require additional data, the data is specified through the `inParameterData` and `inParameterLength` parameters. If no additional data is required you can specify NULL and 0.

Example:

```
slotNumber = 1;
tx_packet = rdm_make_command (dmx_controller,
                              slave_UID,
                              subDevice,
                              GET_COMMAND,
                              SLOT_DESCRIPTION,
                              &slotNumber,
                              2);
```

The `rdm_make_command` routine returns a pointer to the RDM packet.

Note that memory for this packet is allocated within the `DMX_HANDLE` structure. There is no need for the application to release the memory explicitly - i.e. don't call `free` or a similar routine. Equally, be aware that a new call to `rdm_make_command` will overwrite any data stored by the previous call.

(b) The `rdm_send_packet` routine is used to send an RDM packet over the DMX512 connection.

Function Prototype:

```
DMX_ERROR rdm_send_packet (DMX_HANDLE inHandle,
                           RDM_PACKET *inPacket);
```

(c) The `rdm_get_response` routine is used to wait for the reply to an RDM command.

Function Prototype:

```
DMX_ERROR rdm_get_response (DMX_HANDLE inHandle,
                            RDM_PACKET *inPacketSent,
                            RDM_PACKET **outPacketReceived,
                            boolval inAllowNACK);
```

Notice that the second parameter is a pointer to the packet to which a reply is expected. The routine uses this information to make sure that the reply matches what's expected in terms of RDM packet number, reply type, etc.

A pointer to the received packet is returned via the third parameter. This may be NULL on error.

Like `rdm_make_command` there is no need to free the received packet after it is finished with. The memory is allocated internally to the DMX controller and will be reused for the next received packet.

Example Code

The following code shows a more complete example using the DMX controller software. It includes the following steps:

- Initialise the controller
- Perform an RDM discovery process
- Send an RDM packet to ask the first slave for its software version string
- Send a NULL Start-Code packet

For clarity some error checking has been omitted.

```
#include "dmx.h"
#include "dmx_controller.h"
#include "dmx_support.h"

void dmx_demonstration (void)
{
    DMX_HANDLE          dmx_controller;
    RDM_UID             UID;
    DMX_ERROR           errcode;
    DMX_SLAVE_RECORD    *slave;
    int                 attempt;
    RDM_PACKET          *tx_packet, *rx_packet;
    uint_8              slot_values [1];

    /* Initialise controller */
    UID.manufacturerID = FREESCALE_ESTA_MANUFACTURER_ID;
    UID.deviceID = 0x10000000;

    dmx_controller = dmx_controller_init (0, 1, UID);
    if (dmx_controller == NULL)
        return;

    /* Initialise controller hardware */
    dmx_device_init (dmx_controller);
```

```
#ifdef SUPPORT_DEBUGGING
    /* Set debugging level */
    dmx_set_debug_level (dmx_controller, DEBUG_PACKETS);
#endif

    /* Say we want to use checksumming of NULL Start-Code packets
       for extra reliability */
    sip_set_checksumming (dmx_controller, true);

    /* Perform RDM discovery process to find out which slaves
       are present */
    rdm_discovery (dmx_controller, true);

    /* Allocate DMX512 start addresses to any slaves without one */
    rdm_allocate_dmx_addresses (dmx_controller);

    /* Ask the first slave what its software version is... */
    slave = dmx_find_nth_slave (dmx_controller, 0);
    if (slave == NULL)
        return;

    for (attempt = 0; attempt < 3; attempt++) {
        /* Make the GET SOFTWARE_VERSION_LABEL command */
        tx_packet = rdm_make_command (dmx_controller,
                                      slave->slave_UID,
                                      slave->subDevice,
                                      GET_COMMAND,
                                      SOFTWARE_VERSION_LABEL, NULL,
                                      0);

        /* Send it */
        errcode = rdm_send_packet (dmx_controller, tx_packet);
        if (errcode != ERR_DMX_OK)
            continue;

        /* Any response? */
        errcode = rdm_get_response (dmx_controller,
                                    tx_packet,
                                    &rx_packet,
                                    false);

        if (errcode == ERR_DMX_OK) {
            // ... Do something with the software version string here...
            break;
        }
    }
```

```
    /* Send DMX512 NULL Start-Code packet */
    slot_values [0] = 99;
    dmx_set_slot_values (dmx_controller,
                         slave->startAddress,
                         1,
                         slot_values, true);
}
```

Using DALI on the Controller Board

This section will discuss how to use the DALI controller from application software, looking at some of the main routines. For a complete example, see the end of the section.

Initialising the DALI_HANDLE

The public interface to the DALI software uses an opaque data type `DALI_HANDLE`. Application software should begin making a call to `dali_controller_init` to allocate a new handle:

Function Prototype:

```
DALI_HANDLE dali_controller_init (uint_16 inDeviceNumber);
```

In principle the software could support multiple DALI connections if the hardware allowed it.

Initialising the hardware

After the `DALI_HANDLE` has been initialised, the application should call the routine `dali_device_init` to initialise the hardware interface.

Function Prototype:

```
DALI_ERROR dali_device_init (DALI_HANDLE inHandle);
```

Note that the controller board software to accompany the *LightingDemo* application allows the user to switch between DALI and DMX512 protocols dynamically. This is achieved by calling `dali_device_init/ dali_device_deinit` and the DMX512 equivalents as appropriate.

DALI Discovery

To perform an DALI discovery process in order to find out which slaves are attached to the DALI network, call the `dali_discovery` routine

Function Prototype:

```
DALI_ERROR dali_discovery (DALI_HANDLE inHandle);
```

This will cause the controller software to initiate DALI discovery, searching the 24-bit DALI 'random-address' address space for enabled devices. For each slave that is found, the software will request additional information such as the type of LED and whether the device already has a DALI Short Address.

The result is added to a linked list of all known slaves, in which each item has the following structure.

```
typedef struct DALI_SLAVE_RECORD {
    uint_8      shortAddress;              /* DALI short address */
    uint_32     randomAddress;             /* DALI random address at which
                                              slave responded */
    uint_8      modelID;                   /* Type code uniquely
                                              identifying LED type */
    struct DALI_SLAVE_RECORD *next;        /* Linked list of records */

} DALI_SLAVE_RECORD;
```

The following convenience routines allow you to walk the slave list:

(d) Return count of the number of slave records found.

```
uint_32 dali_count_slaves (DALI_HANDLE inHandle);
```

(e) Return pointer to first slave record, or NULL if no slaves found

```
DALI_SLAVE_RECORD *dali_slave_list (DALI_HANDLE inHandle);
```

(f) Return pointer to Nth slave (starting from 0), or NULL if no such record exists.

```
DALI_SLAVE_RECORD *dali_find_nth_slave (DALI_HANDLE inHandle,
                                        int inIndex);
```

During the DALI discovery process the controller will also allocate a DALI Short Address (0 - 63) to any slave which does not have one.

Specifying CIE1931 Colour Space values

The routine `dali_set_chromaticity` allows the application to control the chromaticity and luminance of a slave device. It takes an `(x,y)` chromaticity coordinate and a `Y` luminance value as arguments. The luminance argument is in the range 0.0 to 1.0 to request 0 - 100% of the maximum lumens that the slave can deliver at the requested chromaticity.

Function Prototype:

```
DALI_ERROR dali_set_chromaticity (DALI_HANDLE inHandle,
                                  DALI_SLAVE_RECORD *inSlave,
                                  double in_x,
                                  double in_y,
                                  double in_Y);
```

Sending other DALI commands

The set of commands defined by the DALI protocol can be divided into four categories:

- Direct commands instructing the ballast to switch to a specified power level 0-255
- Normal DALI commands for which a response is not expected - e.g. `OFF`, `STEP UP`
- Query commands for which a response is expected, e.g. `QUERY STATUS`
- Special commands sent to all devices, e.g. `PROGRAM SHORT ADDRESS` (only the ballast which has been previously selected responds)

(a) For the first three categories the two-byte DALI command format is:

```
YAAAAAAS XXXXXXXX
```

where:

`S = 0` : Direct power level
`S = 1` : DALI command

If the command is sent to an individual ballast, `Y = 0` and `AAAAAA` = ballast short address (0 - 63)
If the command is sent to a group of ballasts, `Y = 1` and `00AAAA` = group address (0 - 15)

To send these commands, application software can use `dali_send_normal_command`:

Function Prototype:

```
DALI_ERROR dali_send_normal_command (DALI_HANDLE inHandle,
                                     uint_8 inAddress,
                                     uint_8 inCommand);
```

For example, to send a direct power level command to the individual ballast with short address 5:

```
addressByte = (5 << 1);
dali_send_normal_command (dali_controller, addressByte, 100);
```

To send the command `OFF` to the same ballast:

```
addressByte = (5 << 1) | 1;
dali_send_normal_command (dali_controller, addressByte, DALI_OFF);
```

(b) If a response from the DALI slave is expected the application should immediately follow this up with a call to `dali_wait_response`:

Function Prototype:

```
DALI_ERROR dali_wait_response (DALI_HANDLE inHandle,
                               uint_16 *outResponse);
```

Note that DALI responses are only ever 8 bits, but for certain DALI commands the slave sends no response at all if the answer to a query is ‘no’. In order to accommodate this, the

`dali_wait_response` returns a 16-bit response value where `RESPONSE_NO` (value 0x100) indicates that no response was received.

(c) DALI special commands can be sent using the following subroutine:

Function Prototype:

```
DALI_ERROR dali_send_special_command (DALI_HANDLE inHandle,
                                      uint_8 inCommand,
                                      uint_8 inByte2);
```

The following example sends the `DATA TRANSFER REGISTER` command to all devices instructing them to load the DTR register with the value 100:

```
dali_send_special_command (dali_controller,
                           DALI_SC_DATA_TRANSFER_REGISTER,
                           100);
```

Example Code

The following code shows a more complete example using the DALI controller software. It includes the following steps:

- Initialise the controller
- Perform an DALI discovery process
- Send a DALI packet to ask the first slave for its device type
- Send direct power control instruction to the first slave

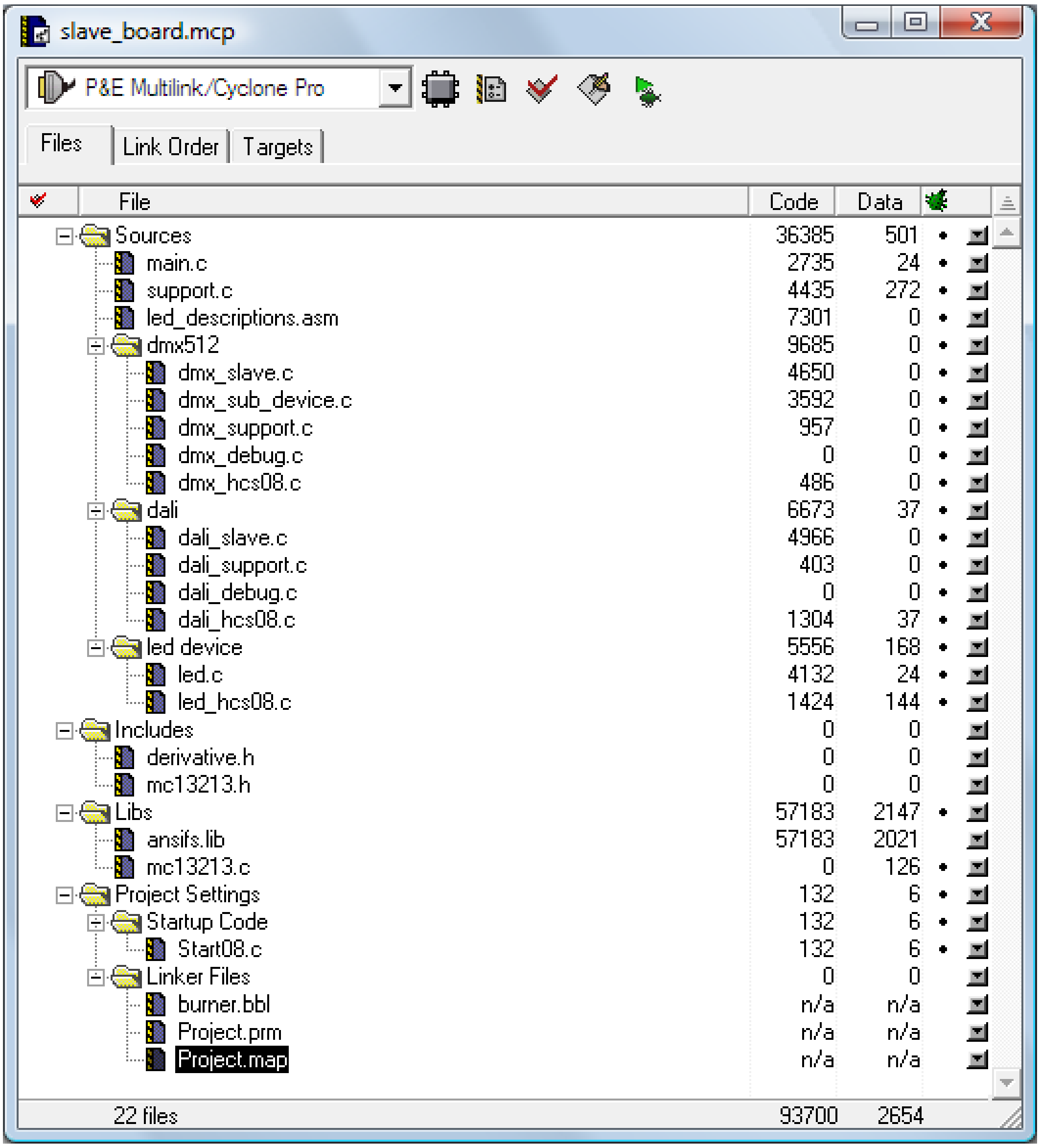
For clarity some error checking has been omitted.

```
#include "dali.h"
#include "dali_controller.h"
#include "dali_support.h"

void dali_demonstration (void)
{
    DALI_HANDLE         dali_controller;
    DALI_ERROR          errcode;
    DALI_SLAVE_RECORD   *slave;
    int                 attempt;
    uint_8              addressByte;
    uint_16             response;

    /* Initialise controller */
    dali_controller = dali_controller_init (0);
    if (dali_controller == NULL)
        return;

    /* Initialise controller hardware */
    dali_device_init (dali_controller);

#ifdef SUPPORT_DEBUGGING
    /* Set debugging level */
    dali_set_debug_level (dali_controller, DEBUG_PACKETS);
#endif

    /* Perform DALI discovery process to find out which slaves
       are present */
    dali_discovery (dali_controller);

    /* Ask the first slave what its device type is... */
    slave = dali_find_nth_slave (dali_controller, 0);
    if (slave == NULL)
        return;

    for (attempt = 0; attempt < 3; attempt++) {
         /* Send QUERY DEVICE TYPE command */
        addressByte = (uint_8) (((slave->shortAddress) << 1) | 1);
        errcode = dali_send_normal_command (dali_controller,
                                            addressByte,
                                            DALI_QUERY_DEVICE_TYPE);
        if (errcode != ERR_DALI_OK)
            continue;

        /* Any response? */
        errcode = dali_wait_response (dali_controller, &response);

        if (errcode == ERR_DALI_OK) {
            //... Do something with the device type information here...
            break;
        }
    }
```

```
    /* Send direct power instruction to first slave */
    addressByte = (uint_8) ((slave->shortAddress) << 1);
    errcode = dali_send_normal_command (dali_controller, addressByte, 100);
}
```

Slave Board Software

The following screen snapshot shows the files used to implement the application on the slave board. If you are building a product based on this software you will probably want to remove either the DMX512 or DALI code as appropriate.



The ansifs.lib Library

The application makes use of floating point data types to calculate colour balancing parameters and hence requires the support of the `ansifs.lib` library which incorporates software floating point routines. In the `ansifs.lib` library, the `double` data type is represented in the 4-byte IEEE754 format.

C Pre-processor Definitions for the slave board

The Slave board software can be built in a number of configurations:

- DMX512 slave, DALI slave or both
- A mini-DALI version which occupies only 8K of Flash and 512 bytes of RAM
- Code to run on the actual board, or code running in the 'simulator' option used by the *LightingDemo* application

These build options are controlled by C pre-processor macros.

The following are defined through the CodeWarrior Compiler for HC08 Target Settings panel...

(a) To enable/disable DMX512/RDM support

```
#define DMX_SLAVE   1
```

or

```
#undef DMX_SLAVE
```

(b) To enable/disable DALI support

```
#define DALI_SLAVE   1
```

or

```
#undef DALI_SLAVE
```

(c) To enable the mini-DALI version

```
#define MINI_DALI 1
```

(d) To specify whether the code runs on actual hardware or in the simulator

```
#define SLAVE_BOARD   1
```

or

```
#define SIMULATED_BOARD   1
```

Mini-DALI version of the slave software

The slave software can also be built in a mini-DALI version which has a very small memory footprint: 8K of Flash and 512 bytes of RAM for the complete application.

This version allows a monochrome LED to be controlled using DALI commands. Compared to the full slave software it lacks the following features:

- Colour control
- Thermal regulation
- Control via the DMX512 / RDM protocol instead of DALI
- XML description of LED characteristics

All of the source files used by the mini-DALI version are the same ones used for the full version with the exception of two files:

`main.c`	is replaced by	`mini_dali_main.c`

`led_hcs08.c` is replaced by `mini_dali_hcs08.c`

A separate CodeWarrior project is provided for building the mini-DALI version.

LED Control

A typical LED package consists of three or four separately controllable colours, e.g. Red, Green, Blue and White.

Each colour, or channel, is controlled by a separate power stage on the slave board. The 'fully-on' current and voltage used by the LED channel are determined by hardware on the board (including current-limiting resistors to prevent LED damage). Colour control is achieved by using a PWM signal to control the channel current, varying the duty cycle in order to vary the brightness of the LED.

The topic of colour balancing is discussed in more detail below.

XML Descriptions of LED Types

In order to perform colour balancing and thermal regulation, the slave board software needs to know the characteristics of each LED package. This information is stored in an easy-to-maintain XML format, stored in Flash on the slave.

The same XML description is also used by the *LightingDemo* application on the PC for two purposes...

- When using the DMX512 RDM protocol, the controller board is able to interrogate the slave in order to determine the LED name, manufacturer, number of primaries, etc. This information is passed on to the *LightingDemo* application running on the PC.

  However, this is not possible in DALI because the DALI protocol only supports single byte responses from slave to controller. For DALI only, the *LightingDemo* application reads the information directly from its own copy of the XML file.

- When simulating a controller board and slave boards in software on the PC, the XML file is used to determine the LED characteristics.

A typical XML description of an LED is as follows:

```
<!--============================================
      Luminus PhlatLight CBM-380
   =============================================-->
 <led>
     <id>2</id>
     <name>PhlatLight CBM-380</name>
     <manufacturer>Luminus</manufacturer>
     <max_current>32.0</max_current>
     <board_type>1</board_type>
     <temperature_matrix>
         0.635 0.156 0.158 0.091
         0.169 0.595 0.103 0.126
         0.158 0.094 1.113 0.158
         0.116 0.130 0.183 0.742
     </temperature_matrix>
     <channel>
         <!--   Red: Luminus PhlatLight CBM-380  -->
         <color>Red</color>
         <pwm_channel>1</pwm_channel>
         <forward_current>12.0</forward_current>
         <forward_voltage>2.3</forward_voltage>
         <flux>700.0</flux>
         <cie1931_x>0.701</cie1931_x>
         <cie1931_y>0.299</cie1931_y>
         <max_temperature>80</max_temperature>
     </channel>
     ... other channels follow
 </led>
```

<id>

Software on the slave board reads the two hardware switches labelled 10’s and 1’s to obtain an LED type in the range 1 - 99. This is matched against the <id> tag to determine which type of LED is connected.

<max_current>

For some LED packages, driving all the LED channels at 100% duty cycle will exceed the maximum rated current for the LED, even though the individual channels are all in range. For example the Luminus PhlatLight CBM-380 allows 12A, 12A, 8.1A and 9A for the Red, Green, Blue and White channels individually, but only allows a maximum of 32A in total.

A value of 0 can be specified if this problem does not exist.

<board_type>

Possible values are 0 for the low-power board and 1 for the high-power board. This information is used by the software to determine how to control the Enable signals to the board’s drive stages.

<temperature_matrix>

This matrix is used in temperature calculations. See the section “Temperature Regulation” for more details.

<channel>

The channel tag should be repeated once for each independently controlled LED primary in the package. The channels should be listed in the same order as they will occur in the DMX512 footprint.

<pwm_channel>

Specifies which of the PWM channels is used to control this device. Possible values are 1 - 4 for TPM2CH1 - TPM2CH4. This information is used in the routine `led_update_power_levels`.

<forward_current>

Specifies the forward current (in Amps) which the LED channel uses at 100% PWM duty cycle.

<forward_voltage>

Specifies the forward voltage (in Volts) corresponding to the forward current value. The software uses these two values to calculate power dissipation at 100% PWM duty cycle in order to perform thermal regulation.

<flux>

Specifies the luminous flux (in Lumens) produced at 100% PWM duty cycle. This information is used for colour balancing.

<cie1931_x> and <cie1931_y>

Specify the `(x,y)` chromaticity coordinates of the LED. Both values are in the range 0.0 - 1.0. This information is used for colour balancing.

<max_temperature>

Specifies the maximum junction temperature for the LED channel. See the section “Temperature Regulation” for more details.

Regenerating the XML File

The XML descriptions are held in a source file `led_descriptions.xml` which needs to be stored in Flash on the slave board.

Unfortunately, the standard version of CodeWarrior for the slave board cannot include an arbitrary binary file (you need to buy a ‘bean’ to let you do this), so some way is needed of including the XML descriptions in the build.

The solution used here is to use a separate utility to convert the XML file into an assembler source file `led_descriptions.asm` containing ASCII strings, e.g.

```
dc.b    "        <id>1</id>"
dc.b    "        <name>Luxeon Rebel RGB + CW</name>"
dc.b    "        <manufacturer>Philips Lumileds</manufacturer>"
```

The utility is a small .exe program that runs at the Windows command prompt.

```
make_xml_asm  <XML file> <assembler file>
```

Full source code of the utility is included in the `xml_utility` folder.

Colour Balancing

Colour balancing is performed by the routine `led_convert_xy_to_levels`.

The CIE 1931 Colour Space chromaticity coordinate (`x, y`) and luminance value `Y` are related to the equivalent `XYZ` tristimulus values by the following equations:

```
x = Y / (X + Y + Z)
y = Y / (X + Y + Z)
```

Or, re-arranging:

```
X = (Y / y ) x
Z = (Y / y) (1 - x - y)
```

The routine begins by computing the `XYZ` tristimulus values of the target colour.

Using the information from the XML description of the LED, the software can also calculate the tristimulus values of the individual primaries like Red.

The next step is to consider the simplified case of a package with only three primaries - e.g. consider Red, Green and Blue, and ignore any White channel. The software needs to calculate the duty cycles (in the range 0.0 - 1.0 for 0-100%) needed for each channel in order to achieve the target chromaticity at maximum brightness.

The `XYZ` value of the target colour and the duty cycles are related by a matrix multiplication:

$$\left\{ \begin{array}{c} X \\ Y \\ Z \end{array} \right\} = M \times \left\{ \begin{array}{c} \text{Duty Cycle Red} \\ \text{Duty Cycle Green} \\ \text{Duty Cycle Blue} \end{array} \right\}$$

Software needs to determine the 3 x 3 matrix `M` and then compute the inverse of `M` in order to calculate the duty cycles required.

`M` can be determined from the `XYZ` tristimulus values of the primaries. For example when only the Red primary is illuminated using 100% duty cycle, it produces the lumens and `(x, y)` chromaticity

specified in the XML description. For the Luminus PhlatLight CBM380 example given earlier these are `Y` = `700` lumens and `(x,y) = (0.701, 0.299)`.

Converting these to `XYZ` we have:

$$\begin{Bmatrix} Xred \\ Yred \\ Zred \end{Bmatrix} = \mathrm{M} \times \begin{Bmatrix} 1 \\ 0 \\ 0 \end{Bmatrix}$$

It follows that the entire matrix M is simply:

$$\begin{Bmatrix} Xred & Xgreen & Xblue \\ Yred & Ygreen & \mathrm{Yblue} \\ Zred & Zgreen & Zblue \end{Bmatrix}$$

Having calculated the required duty cycles, one or more values may turn out to be negative. This happens when the target colour is outside the triangular gamut of all possible colours that can be produced by mixing the three LED primaries. In this case the colour is adjusted so that it is in-gamut by adding just enough to bring the colour to the edge of the triangle.

The discussion above considered the simplified case of only three primaries. Many LED packages have four primaries - e.g. Red, Green, Blue and White. Effectively this means that matrix M has three rows but has four columns - i.e. it is 3 x 4 instead of 3 x 3, meaning that there is no unique solution to the colour-balancing problem.

The software on the slave board considers the four primaries in groups of three-at-at-time, e.g. Red/Green/Blue, Red/Green/White, Red/Blue/White and Green/Blue/White. The target colour can normally be represented by either of two of these combinations, so the software chooses a solution that will deliver maximum brightness.

Adjusting Duty Cycles

The routine `led_convert_xy_to_levels` discussed above will calculate the duty cycles necessary to achieve the target colour at maximum brightness. These duty cycles may need to be scaled back:

(a) Because the application software requested a luminance value of less than 100%

(b) Because driving the LED package with the calculated duty cycles would exceed its maximum rated current

(c) Because driving the LED package with the calculated duty cycles would cause it to overheat.

Adjustment takes place in the routine led_update_power_levels, which is also responsible for programming the PWM module and controlling the Enable signals to the LED power stages.

Temperature Regulation

Driving too much current through an LED for too long can cause it to overheat, shortening the working life of the LED or even damaging it. In order to avoid this it is necessary to monitor the temperature and reduce the power if necessary.

Each channel of a multi-colour LED package will have a maximum recommended junction temperature. For example the PhlatLight CBM-380 maximum junction temperature for Red is 80°C. These values are specified by the <max_temperature> tags in the XML file.

The junction temperatures of an LED package cannot be measured directly. Instead they must be calculated by measuring an accessible temperature (e.g. the heat sink temperature) using a thermistor, and then calculating the junction temperatures using the power dissipation for each channel and a 4x4 matrix PM.

$$\left\{\begin{matrix}\text{TJunction Red}\\ \text{TJunction Green}\\ \text{TJunction Blue}\\ \text{TJunction White}\end{matrix}\right\} = \text{Tthermistor} + \text{PM} \times \left\{\begin{matrix}\text{Power Red}\\ \text{Power Green}\\ \text{Power Blue}\\ \text{Power White}\end{matrix}\right\}$$

The PM matrix is the power-to-temperature matrix as recommended by the LED manufacturer and read from <temperature_matrix> tag in the XML file. For example, for the Luminus PhlatLight CBM-380 the matrix is:

```
0.635 0.156 0.158 0.091
0.169 0.595 0.103 0.126
0.158 0.094 1.113 0.158
0.116 0.130 0.183 0.742
```

The matrix contains thermal resistance values. Note that the temperature of each LED junction does not just depend on the heat sink temperature and its own thermal resistance - there is cross-talk between the channels. For example if the Green LED is being driven, it causes the Red LED junction to heat up.

The Power figure for each LED is calculated as follows:

Power = Forward Voltage x Forward Current x Duty Cycle

Because the Forward Voltage and Forward Current are fixed by hardware it is not necessary to do the complete multiplication every time. Instead they can be used to compute a new version of the PM matrix PM' so that the junction temperatures can be calculated by the following equation:

$$\begin{Bmatrix} \text{TJunction Red} \\ \text{TJunction Green} \\ \text{TJunction Blue} \\ \text{TJunction White} \end{Bmatrix} = \text{Tthermistor} + \text{PM}' \times \begin{Bmatrix} \text{Duty Cycle Red} \\ \text{Duty Cycle Green} \\ \text{Duty Cycle Blue} \\ \text{Duty Cycle White} \end{Bmatrix}$$